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Present Practice of Using Nautical Depth to Manage Navigation Channels in the Presence of Fluid Mud

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PURPOSE: The U.S. Army Corps of Engineers (USACE) Dredging Operations and Environmental Research (DOER) Program, in conjunction with the Monitoring Completed Navigation Projects (MCNP) program, is conducting research and development activities aimed at implementing the practice of using nautical depth to manage navigation channels in the United States containing fluid mud. In these waterways, compared to those with more consolidated bottom materials (e.g., sand), determining where the *bottom* actually lies for navigation purposes can be difficult. That is because fluid mud, though denser than water, can in certain conditions be navigable. In such cases, the depth of interest is the distance between the water surface and the *nautical bottom*, referred to as the *nautical depth*. Using the nautical depth to manage navigation channels and ports requires a mud property that determines a navigability criteria, a practical method for surveying that property, and knowledge of ship-specific behavior in that fluid mud. This technical note describes (1) the nautical depth approach, (2) its present use for managing navigation channels, (3) issues related to conducting hydrographic surveying in waterways with fluid mud bottoms, (4) the newest developments in survey instrumentation, (5) a recent study of ship behavior in fluid mud, and (6) current USACE activities being conducted to implement the use of nautical depth in the United States.

INTRODUCTION: Fluid mud is a high-concentration aqueous suspension of fine-grained sediment in which settling is substantially hindered by the proximity of sediment grains and flocs but which has not formed an interconnected matrix of bonds strong enough to eliminate the potential for mobility, leading to a persistent suspension (McAnally et al. 2007a). It can be characterized as suspensions with density gradations ranging from slightly greater than that of the overlying water in its upper layers to that of stiff, dense, lower layers with mud densities ranging from 1,100 to 1,350 grams per liter (g/L). It consists of silt and clay-sized material with clay minerals and organic material in concentrations ranging from 50 to 500 g/L or 2% to 13% solids by volume (Teeter 1997).

In navigation channels with *solid* bottoms (e.g., sand), an under-keel clearance (distance between the keel and channel bottom) is used to account for safety factors such as ship motion from waves, squat, bottom obstructions, etc., to avoid contact between the ship and bottom. In channels with fluid mud, the following is stated per PIANC (1997):

> Although the upper part of the mud layer has a somewhat higher density than that of water, its rheological properties are comparable with those of water, so that a ship's hull suffers no damage when it penetrates this interface. Even navigation with an under-keel clearance which is negative referred to the interface can be considered, which implies that the ship's keel is permanently in contact with the mud. On the other hand, safety of navigation

> requires that the pilot must always be able to compensate for the effects of mud on ship behavior by means of its own control systems or external assistance (e.g., tugs).
>
> An acceptable compromise between the safety of navigation and the cost of channel maintenance can only be reached by introduction of non-conventional definitions and survey methods, and requires additional knowledge about the navigational response of ships in muddy water.

Note that the 1997 PIANC definition refers to an apparent "negative" underkeel clearance as defined by older acoustic-only measurement methods. To properly implement this alternative approach, the terms *bottom* and *depth* can be modified to nautical bottom and nautical depth where nautical bottom is defined (PIANC 2014) as

> the level where physical characteristics of the bottom reach a critical limit beyond which contact with a ship's keel causes either damage or unacceptable effects on controllability and maneuverability

and nautical depth as

> the instantaneous and local vertical distance between the nautical bottom and the undisturbed free water surface.

The role of the USACE with respect to navigation is to provide safe, reliable, and efficient waterborne transportation systems (e.g., channels, harbors, waterways) for movement of commerce, national security needs, and recreation. Fluid mud poses a significant challenge. McAnally et al. (2007a) report that fluid mud was once thought to occur in only a few locations (e.g., Europort in The Netherlands, Savannah Harbor in the U.S.); "however it now appears to be a common, perhaps even ubiquitous, feature of water bodies laden with fine-grained sediment." Herbich et al. (1989) conducted a survey of U.S. ports and USACE Districts to evaluate the number of harbors and channels experiencing fluid mud conditions and determined that "a high percentage of responses clearly indicated that many U.S. ports experience fluid mud problems and presently no uniform procedure to accurately define the channel depth is practiced."

The difficulties in determining depth when fluid mud is present have hindered USACE efforts to optimize maintenance dredging in fluid mud channels in the United States. An operational definition of the nautical channel bottom in areas with fluid mud, based on density or other rheological parameters, could reduce maintenance dredging costs (Kirby and Parker 1974; De Mayer and Malherbe 1987; Herbich et al. 1989, 1991; Teeter 1992). Herbich et al. (1989) report that "the 'navigable' or 'nautical' depth concept is practiced unofficially in many U.S. ports as the pilots guide ships through channels that contain fluid mud layers." However, no official U.S. criteria have been developed, either in terms of density, shear strength, or acoustic survey results, to adequately define the navigable depth.

THE NAUTICAL BOTTOM APPROACH: To complete the definition of nautical bottom, the physical characteristic on which the "critical limit" criterion is based and the criteria for "acceptable" ship behavior referred to in PIANC (2014) should be provided. Consequently, from a practical and operational perspective, PIANC (2014) recommends that implementation of a nautical bottom includes the following:

- "a practical criterion, i.e., selection of the physical mud characteristic acting as a parameter for the nautical bottom approach and its critical value"
- "a practical survey method to determine both the acceptable level and the water-mud interface in an efficient and reliable way"
- "a minimum value for the required under-keel clearance relative to this nautical bottom"
- "if required, either a minimum value for the required under-keel clearance relative to the water-mud interface to ensure a minimal risk for contact and acceptable ship behavior, or a maximum value for the penetration of the keel into the mud layer if contact with the mud is considered to be acceptable according to local conditions"
- "knowledge about and training in ship behavior in these situation, and if necessary, measures to compensate for adverse effects on controllability and maneuverability."

Unacceptable effects on vessel controllability and maneuverability from contact with fluid mud are caused by the additional forces exerted upon the vessel by that fluid mud, and these forces are related to the fluid mud's rheology (USACE 1954; De Mayer and Malherbe 1987; Teeter 1992; Herbich et al. 1989, 1991; PIANC 1997; Vantorre et al. 2006). Webster's Dictionary defines rheology as a science dealing with the deformation and flow of matter. As such, the nautical depth definition theoretically should be based on rheological properties. However, density has been the predominant property used to define nautical depth. This is because, since the inception of nautical depth, density has been a property of fluid mud that existing survey equipment could readily measure. While innovative technologies that incorporate other physical properties such as shear strength are emerging, density was originally proposed for Rotterdam by Kirby and Parker (1974) and remains world wide as the dominant property upon which nautical depth is based. Table 1 lists world-wide density criteria currently in use.

Table 1. World-wide nautical depth density criterion critical limits (adapted from PIANC 2008).

Country	Port	Density (g/cm^3)*
The Netherlands	Rotterdam	1.2
Thailand	Bangkok	1.2
Surinam	Paramaribo	1.23
Belgium	Zeebrugge	1.2
China	Yangtze	1.25
China	Liang yungang	1.25 – 1.3
China	Tianjing xingang	1.2 – 1.3
UK	Avonmouth	1.2
France	Dunkirk	1.2
France	Bordeaux	1.2
France	Nantes - Saint Nazaire	1.2
Germany	Emden	1.22 – 1.24
French Guyana	Cayenne	1.27
UK	Bristol	1.2

*grams per cubic centimeter

De Mayer and Malherbe (1987) wrote that "from the point of view of the definition of the nautical bottom it is rather obvious to take shear properties of the mud layer into account" and that "a nautical bottom has to indicate a discontinuity which coincides with a characteristic level in the deposit where mud properties change." From the analyses of initial rigidity and dynamic viscosity parameters on fluid mud from Zeebrugge, Belgium, it is suggested that the nautical bottom be defined by the transition from

- "the first behavior domain where maneuvering characteristics are poorly or not affected by the concentration of the deposit and are rather similar to those in pure water to
- the second behavior domain where maneuvering characteristics are strongly affected by the concentration values of the deposit and are consequently different from those in pure water."

While density and viscosity are related, that relationship can be complicated by other factors (Teeter 1992). The factors include (PIANC 1997) the following:

- stress history
- sand content
- particle diameter
- clay mineralogy
- rate of deformation (shear rate)
- percentage of organic material
- water chemistry (especially pH, salinity, etc.).

Implementation of *conventional* nautical depth involves dredging to the density horizon specified by the density critical limit criteria. However, in the right site-specific conditions, it may be possible to use sediment conditioning to improve fluid mud navigability by reducing its shear strength. Sediment conditioning is different from conventional nautical-depth management practice in that the fluid mud is not removed from the dredging template, but rather it is subjected to some form of external force(s) and exposed to air to breakdown the interparticle structure to reduce shear stress, viscosity, and/or density. At Emden, Germany, sediment conditioning is accomplished by (1) pumping the fluid mud up from the bottom at relatively low energy levels with a modified hopper dredge, (2) turning the fluid mud over in the hopper where it is exposed to air, (3) then returning it to the bottom (Wurpts 2005).

Whereas fluid mud viscosity is shear-rate dependent and depends on the vessel shape, size, and speed, yield stress (or strength) is a less variable property. Yield stress determines the *breaking force* of the fluid mud's resistance to motion against the ship's hull. At Emden, Germany, a yield strength of 70 Pa, which represents a breaking force of 70 Newtons exerted upon a square meter (0.01 pounds per square inch [lb/sq in.]) of the ship's hull, was taken to be the upper limit of navigability; however, Wurpts (2005) determined that a higher value of 100 Pa was acceptable.

CHANNEL SURVEYS IN FLUID MUD

Fluid mud effects on conventional acoustic depth measurement. Hydrographic surveys are usually conducted with either a high- or low-frequency transducer (such as 200 kilohertz [kHz] and 24 kHz, respectively) or a combination of both frequencies (a dual-frequency system). Attenuation of acoustic energy is directly proportional to its frequency, and the depth in fluid mud from which an acoustic pulse reflects is a function of the *sharpness* of fluid mud's density gradient (or rate of change in density), not a specific density value itself. High-frequency acoustic energy will normally reflect from an upper layer of fluid mud even if it has a very low density, and the lower-frequency acoustic energy will register a lower layer if that layer interface has a higher acoustic reflectivity than the upper one. In other words, high-frequency echo sounders (200 kHz and higher) can reflect off the water/muddy water interface (i.e., the lutocline), and (given transmit and sensitivity settings are comparable) the lower frequency echo sounders can reflect off a density gradient (or density gradients) deeper in the fluid mud layer. This phenomenon is illustrated in Figure 1 which shows acoustic returns from a dual frequency echo sounder (200 kHz and 41 kHz). The high frequency return (the sharp trace digitized with a red line) is being reflected from the water/muddy water interface, and the low frequency return (the broad trace digitized with a black line) is reflected from a density gradient deeper in the fluid mud layer.

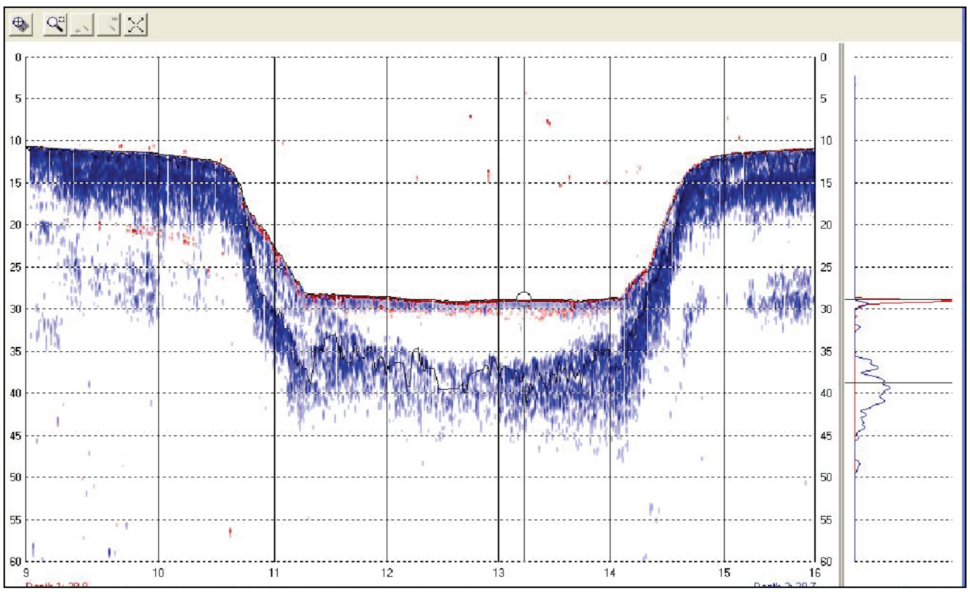

Figure 1. Dual-frequency echo sounder cross section with 200 kHz return signal digitized in red and 41 kHz return signal digitized in black.

McAnally et al. (2007b) reported that for conventional acoustic surveying equipment, "instrument frequencies have been more or less standardized to produce consistent results in hard bottom materials, but their results in fluid mud are inconsistent, since the reflection strength is proportional to density gradient, not a specific density."

Adjustment of the sensitivity control on the echo sounder can affect the interpretation of where the bottom is, and respective reported water depth. The USACE (2013) hydrographic surveying Engineer Manual states that

> An important point to remember is that the amplitude of the first signal return is proportional to the density of the upper layer. Thus, a hard sand surface layer will give a much stronger signal return than a low-density fluff surface layer, no matter what frequency is used. Keeping this fact in mind can be helpful in making a rational setting of

> the sensitivity control on a depth sounder. Consider the situation in which a survey is under way and the depth chart recording begins to print irregularly in a particular area. The natural tendency is to adjust the depth recorder sensitivity control until the depth chart prints a solid line again. Increasing the sensitivity of the recorder permits the chart to print a depth mark on the basis of a signal return from a softer bottom. The potential problem with this type of adjustment is that the higher sensitivity may cause the depth chart to register a 'fluff ' layer and not a true bottom. Thus, do not 'crank up' the sensitivity control to keep a solid line on the recorder and do nothing else. If a sensitivity adjustment is necessary, it is also necessary to make a correlating depth check using one of the alternate depth measurement techniques described in this chapter. If the alternate method agrees with the depth chart, the sensitivity adjustment is probably warranted. If there is no correlation, use of the alternate depth measurement method is indicated (e.g., lead line, nuclear density probe).

PIANC (2008) recommends that if there is a steady increase of density and/or sound velocity with depth, then an echo sounder should not be used. USACE (2013) states that depth records when surveying over waterway bottoms with soft material surfaces cannot be interpreted reliably unless other correlating information is developed.

Surveying of fluid mud properties. At some locations, a reasonable relationship has been found between acoustic reflections and a fluid mud property (PIANC 1997). For example, a 33 kHz reflection generally corresponds to a 1,150 kilograms per cubic meter (kg/m^3) density level in the Loire estuary in France (Broussard et al., n.d.) and acts as a definition for nautical bottom in Antwerp, Belgium (Claessens and Marain 1988). However, remote sensing of seafloor sediment density using measurements of reflected acoustic signals is generally unreliable without site-specific calibration using in situ measurements of fluid mud properties. To accomplish this, various in situ probes have been developed to make the needed measurements.

Nuclear density probes, originally demonstrated by Kirby and Perker (1974) and mentioned in the passage from the Engineer Manual (USACE 2013), use a relationship between the attenuation of radiation and sediment density to measure the density. However, there are certain troublesome restrictions and requirements involved in using an instrument containing a radioactive source. A probe called the DensX™ uses X-rays in similar manner to measure density without the same restrictions. There is also a free-fall impact instrument called the Graviprobe™ that analyses the dynamic behavior of the probe as it penetrates the bottom using accelerometers, inclinometers, and pressure sensors in the probe. The data are processed to yield measurements of density, undrained shear strength, and viscosity. The Advanced Modular Ultrasound System (ADOMUS) uses ultrasound (2 MHz) technology to profile acoustic impedance, sound speed, and acoustic attenuation in fluid mud layers to determine sediment density. The system has been tested in fluid mud in the River Ems.

To be useful for determining the navigability of waterways, spatially comprehensive measurements of fluid mud properties are generally required. For practical reasons, as well as due to the temporal variability of fluid mud, the properties must be able to be measured relatively quickly. Both mechanical and acoustic means of doing so have been developed.

A mechanical fluid survey technique, the Rheocable Method (Druyts and Brabers 2012), utilizes a weighted pressure sensor package connected to a data display deck unit. The sensor package is dragged along the seabed to survey a channel. The viscosity of the mud determines the depth at which the sensor package is dragged and thereby defines a potential definition of the interface between the fluid and the solid mud. The sensor package consists of a pressure sensor placed in a sealed pressure pod with two circulation tubes reaching above the liquid-mud layer to ensure the correct translation of pressure measurements into water depths based on the known density of seawater. The water density is continuously measured at several levels along the umbilical cable using conductivity-temperature-depth (CTD) probes. During postprocessing, pressure/depth is further compensated for atmospheric pressure. Following the sensor package is a short resistivity cable. The resistivity cable is used to verify that the sensor package is traveling on the fluid/solid-mud interface and not floating in it.

An in situ fluid mud properties probe called the RheoTune has been developed by STEMA Survey Services of the Netherlands. The RheoTune is a fluid-mud profiling probe that operates on the *tuning fork* principle, with one of the legs of the tuning fork vibrating at a specific frequency and the other leg vibrating at a frequency and amplitude that depend on the density and rheological properties of the medium in which the probe is inserted. The natural resonant frequency of the vibrating fork sensor decreases as the density of the fluid mud increases, and the amplitude of vibrations decreases with increasing viscosity. Thus, measurements of the frequency and amplitude of the vibrating sensor are processed by the RheoTune and result in independent measurements of density and viscosity. In general, the tuning-fork method of measuring density and viscosity is restricted to Newtonian fluids which continue to flow even when very small forces act on them. Fluid muds of interest in navigation studies generally show non-Newtonian behavior; however, they are enough like a fluid that the non-Newtonian behavior can be accounted for by using a proprietary calibration developed by STEMA. The RheoTune uses a predefined generalized density calibration based on database values from worldwide natural mud materials. Site-specific conditions may call for modifying the density calibration. The vibrations of the tuning fork do not impart enough force on typical muds of navigation interest to produce this effect. However, STEMA found that the amplitude damping effect could be correlated with yield stress. The amplitude damping effect caused by the viscous behavior of the mud appears, from their studies, to be uniform in muds of navigation interest. STEMA created a database that compares the viscous damping of their tuning fork sensor amplitudes with yield-stress values (measured with a rheometer) in muds spanning the range of those of navigation interest. The results of these comparisons are incorporated in the RheoTune calibration, and the RheoTune outputs yield-stress values from its viscosity measurements.

With calibrations using the RheoTune in situ measurements of density and viscosity, an acoustic-based survey system of fluid mud properties was developed. It consists of the STEMA-developed SILAS software for processing acoustic sub-bottom reflection signals in the low-frequency range of 3.5 to 33 kHz. With a standard dual-frequency acoustic survey system and the SILAS software, the depths of given mud density and layers can be surveyed, and charts of contours of those depths can be produced using standard survey methods. Figure 2 shows the 1,200 g/L density depth contours of a section of the Gulfport (Mississippi) Ship Channel.

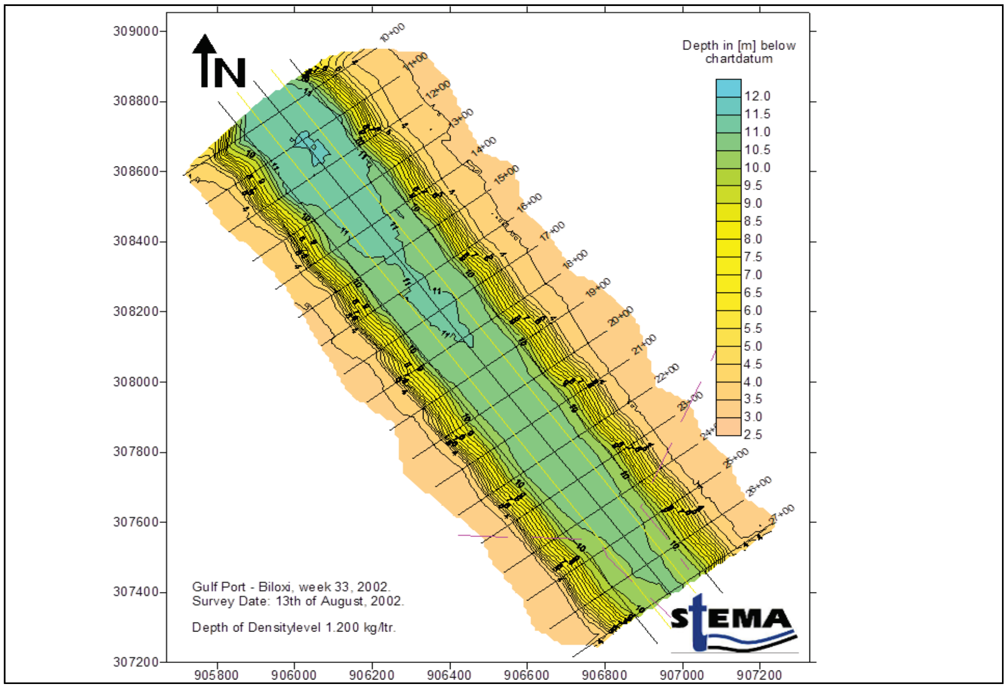

Figure 2. 1200 g/L density contour chart of a section of Gulfport navigation channel.

NAVIGATIONAL RESPONSE OF SHIPS IN FLUID MUD: In general, knowledge of ship maneuverability in fluid mud is achieved through the site-specific experiences of pilots operating ships in areas where fluid mud exists. However, well-documented, quantitative knowledge about the maneuvering behavior of ships in fluid mud navigation areas has been acquired in a comprehensive research project carried out by the Flanders Hydraulics Research, Antwerp, with the scientific support of the Maritime Technology Division at Ghent University. The objective of this research project was to lead to new criteria for determining nautical bottom for Zeebrugge, Belgium, and consisted of laboratory-scale captive maneuvering tests and computer simulations.

The laboratory tests (Delefortrie and Vantorre 2006) were carried out in a shallow-water tow tank equipped with a planar motion carriage (Figure 3). Models of three types of ship hulls were tested; they were a 6,000 Twenty-foot Equivalent Unit (TEU) container carrier, a 283K DWT tanker, and an 8,000 TEU container carrier. Each model was equipped with a propeller and rudder. Mixtures of chlorinated paraffin and petroleum, which allowed both density and viscosity to be controlled within certain ranges, simulated the fluid mud. Density-viscosity profiles of bottom sediments from measurements made in the outer harbor of Zeebrugge from 1997 to 1998 were used to create realistic simulations of fluid mud properties for the model tests. Tests without ship sway or yaw were conducted as bollard pull tests with varying rudder angle and propeller speed and tests with varying forward speed, rudder angle, drift angle, and propeller speed. The tests with harmonic sway and yaw applied were also conducted with variable forward speed, rudder angle, and propeller speed.

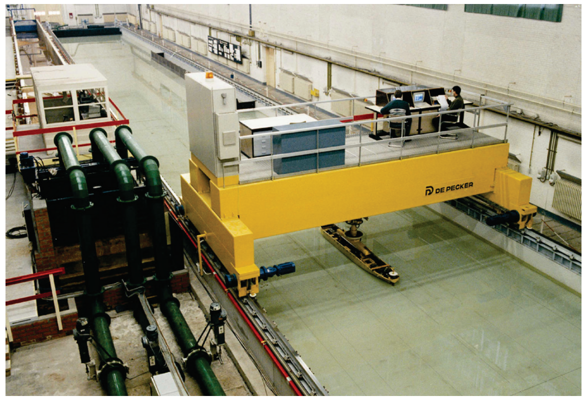

Figure 3. Flanders Hydraulics Research ship towing tank.

A mathematical model of ship maneuvering was developed and calibrated using the data from the laboratory tests (Delefortrie et al. 2005; Delefortrie and Vantorre 2006). The model was applied to direct computer simulations of ship maneuvering in areas of fluid mud (Delefortrie et al. 2005) and implemented in a real-time, full-bridge navigation simulator of Zeebrugge Harbor (Delefortrie et al. 2007). Harbor pilots used the simulator and evaluated the simulated ship behavior in comparison to their experiences in the Harbor.

CURRENT USACE ACTIVITIES TO IMPLEMENT NAUTICAL DEPTH: Implementation of nautical depth activities are currently being conducted by the USACE in the Gulfport (Mississippi) Ship Channel and the Calcasieu (Louisiana) Ship Channel in conjunction with the U.S. Army Engineer District Mobile (SAM) and U.S. Army Engineer District New Orleans (MVN), respectively. SAM and MVN are using the STEMA system (RheoTune and SILAS) to survey the channels. The feasibility of using a ship simulator, similar to the previously described one used for Zeebrugge, is being investigated to augment knowledge and training of ship-specific behavior in channel-specific fluid mud.

A modified sediment-conditioning method was also investigated by the USACE as a variation of implementing nautical depth in the Atchafalaya River Bar Channel (ABC) in Louisiana. A bed leveler was dragged at different depths in the ABC to impart external forces upon the fluid mud bottom to potentially alter its physical properties. This demonstration was one of a series of investigations into nautical depth sediment management methods to improve the navigability of the channel between routine navigation dredging cycles. Measurements of the before-and-after drag density and yield stress profiles (i.e., values relative to depth) were made using the RheoTune. Density horizons were plotted using the SILAS and analyzed to evaluate changes resulting from the drag operations. In regards to density, the plow-barge operations seem to have had no effect, or an extremely limited effect over a short duration. The RheoTune analysis led to the same basic conclusions in regards to yield stresses.

Neither analysis indicated that there was a decrease in yield stress at all stations in the region where the bed leveler was towed, for all 3 feet of bed-leveler depth. The results of the analysis showed that the bed-leveler operations did not effectively decrease yield stress in the fluid mud. Alternative sediment conditioning techniques (e.g., water injection dredge) are currently being considered for potential evaluation in the ABC. More detailed information on the bed-leveler demonstration is documented in Tubman et al.[1] Knowledge and experiences gained from these various activities will be synthesized into engineering guidance for implementation of nautical depth at respective USACE navigation projects (e.g., revised Hydrographic Surveying Engineering Manual).

DISCUSSION AND SUMMARY: Nautical depth is the depth needed by ships to safely navigate channels without damaging the ship's hull or causing unacceptable controllability and maneuverability issues. In the presence of fluid mud, that depth may be such that the ship's keel is moving through bottom-sediment suspensions. One of the most important factors in determining what constitutes *safe* ship passage is experience. However, mariner experience in navigating through fluid mud waterways is at best poorly documented and is subject to bias. Objective, well-documented determination of safe nautical depths to use for managing these waterways would be highly desirable. To achieve this, knowledge of ship behavior in fluid mud is needed and must be related to a fluid-mud property that can be practically surveyed.

At several international ports, a mud density value has been used to define a depth within the fluid mud through which ships can safely navigate. Yield stress, which is a measure of the breaking force of the fluid mud's resistance to motion against the ship's hull is an obvious parameter to consider when defining nautical depth. A yield stress criteria has been successfully applied at Emden, Germany. However, nautical bottom is usually defined on the basis of a critical density. This is because survey systems have been developed that can, in certain locations, produce continuous, wide-area, bottom density data. The STEMA SILAS system is an example of such a system. No similar acoustic survey method exists for rheological data, and defining nautical bottom on the basis of a rheological property such as yield stress or dynamic viscosity must rely on spot measurements.

To achieve true objective determination of nautical depth, it would be highly desirable to have a mathematical model of fluid mud and ship response that could be implemented at a given location with known mud properties, standard ship design parameters, and operating conditions as the only inputs. Progress in this direction was made in a research program applied to the harbor at Zeebrugge, Belgium. However, despite recent efforts to develop objective mathematical models, the use of nautical depth is generally a site-specific practice verified by practical experience.

POINTS OF CONTACT: For additional information on nautical depth and fluid mud, contact Timothy Welp (601-634-2083), *Timothy.L.Welp@usace.army.mil*.

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